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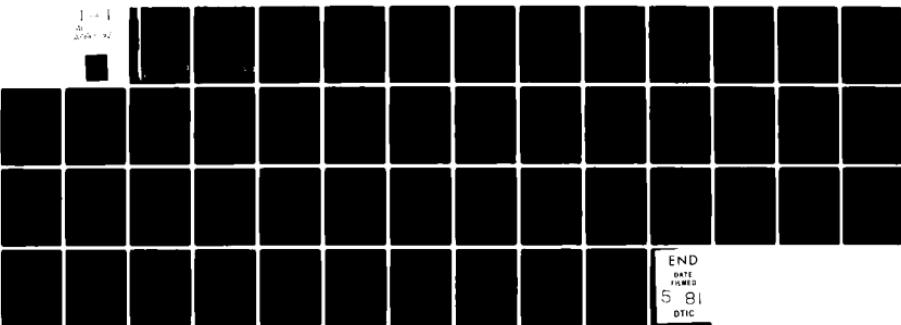
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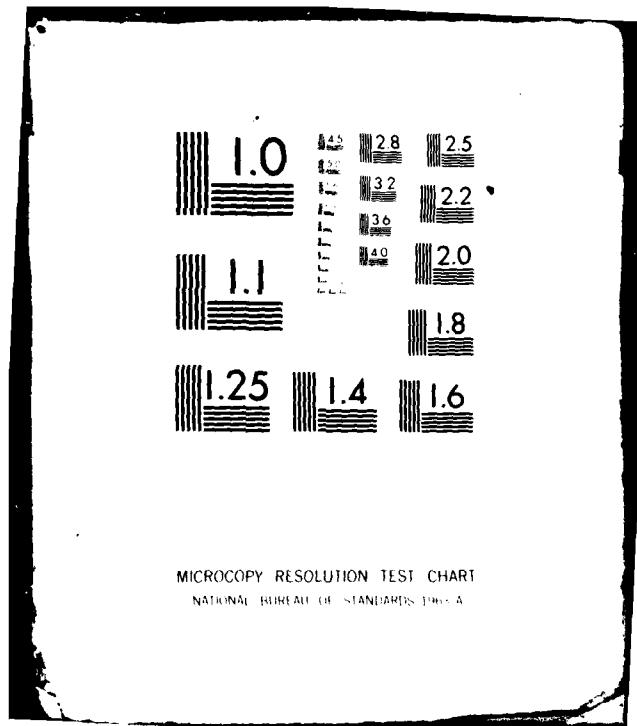
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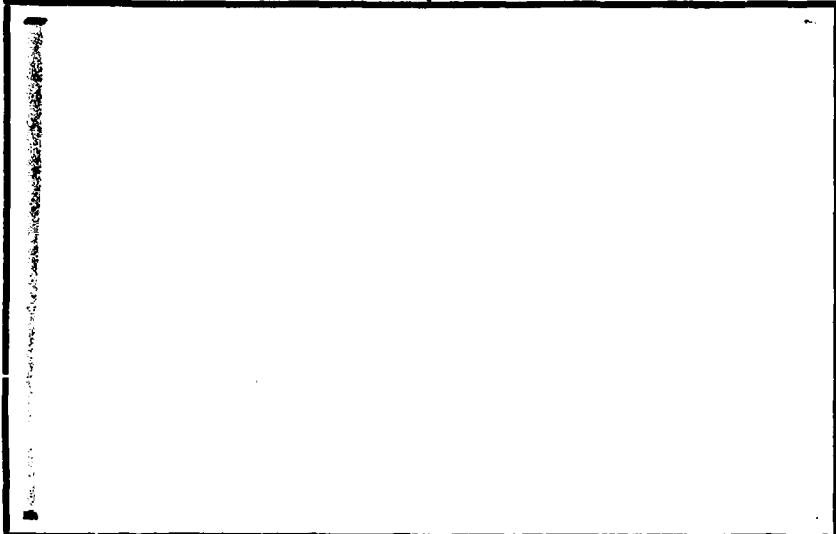


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HOW IS PERFORMANCE LIMITED: TESTING THE NOTION OF
CENTRAL CAPACITY.

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Daniel Gopher

David Navon

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ABSTRACT

Two-dimensional pursuit tracking task was employed in three experiments designed to test three predictions of a central capacity approach to the description of performance limitations under time-sharing conditions. These are the predicted effects of change in task difficulty, task emphasis and their interaction. Each of simultaneously performed tracking dimensions (horizontal and vertical) was treated as a separate task and manipulated independently. Tracking difficulty on each dimension and their relative emphasis were jointly investigated in a central composite response surface design. Negatively accelerated effects of task priority and limited tradeoff between tracking dimensions were obtained when frequency and velocity of target movement served as difficulty parameters. Direct linear tradeoffs were observed when control complexity was increased by changing control dynamics. These results cannot be easily accommodated within a strict central capacity model. An alternative interpretation which relies on a multiple capacity approach is outlined.

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A prevalent interpretation of observed decrements in the performance of time-shared tasks resorts to the notion of a central pool of limited resources, as most explicitly detailed by Kahneman (1973). According to this model, concurrently performed tasks apply demands to a central pool of resources and get supplies in proportions that are related to their relative demands. The notion of central capacity limitation has been generally adopted in various versions by many investigators (e.g. Broadbent, 1971, Kerr, 1973, Moray, 1969, Norman & Bobrow, 1975, Posner & Boice, 1971). However, there seems to be little agreement about what it is or how to go about testing it (cf. Kantowitz, in press). Elsewhere (Navon & Gopher, in press) we discussed in detail the problems with testing this notion. In this paper we present the results of three experiments designed to test some of the predictions that can be derived from a strict model of central capacity, i.e. one which states that the larger part of variability in task performance is due to availability of resources for doing it.

According to this model, the level of performance on a task is determined by how much the performer invests in it on the one hand, and how much that investment can produce on the other hand. In other words, a task is characterized by various parameters which affect the output of a unit of resources (or, if you wish, determine its difficulty), and is allotted at any moment with a certain amount of resources by some considerations which have been termed by Kahneman (1973): allocation policy.

The major alternative explanation to task interference between concurrently performed tasks is that it is due to a conflict between their outputs or side effects or preconditions, or to simultaneous use of the same mechanisms (e.g. Allport,

Antonis and Reynolds, 1972, Welford, 1967). We called this later type of interference "concurrence costs" (Navon & Gopher, in press) and Kahneman labelled it "structural interference".

The central capacity model offers an integrative, parsimonious and powerful approach to the interpretation of time-sharing behavior. It enables derivation of resource demands imposed by any pair of tasks from observing their concurrent interference. It also motivates the drive to develop a general rule to measure task load and operator attention capacity. Supported by experimental evidence of performance interference in the concurrent performance of tasks that differ in the modality, content and pace of processing and response requirement (for a review see Kahneman, 1973), the central pool model gained popularity and acceptance. Still, its usefulness and generality have not been directly confronted.

How does one go about testing capacity interference or evaluating the usefulness of the central capacity notion. One frequent approach is to observe performance decrements from single- to dual-task situations. This is a poor indication for capacity interference, because such decrements may result from other kinds of interference which we elsewhere termed concurrence cost (see Navon & Gopher, in press), or perhaps may be counteracted by a tendency of capacity to stretch in order to accommodate the heavier load (see Kahneman, 1973). A better approach seems to be to change systematically the demand for resources imposed by tasks under time-sharing conditions (similar argument in favor of dual-task manipulation has been suggested by Kantowitz & Knight, 1976).

If time-shared tasks are assumed to compete for allocation of the

same resource, then increasing the priority of one task should increment its share of resources, thereby leading to an improvement in its performance. Simultaneously, the decreased amount of resources allotted to the other task should now lead to a decrement in its performance. If the difficulty levels on the two tasks are maintained at a fixed level and all possible combinations of performance levels on the two tasks arising from splitting the single pool of resources between them in various ratios are represented, we obtain a tradeoff curve of the type called by Norman & Bobrow (1975) Performance Operating Characteristics (POC). This curve depicts the tradeoff of performance between two concurrently performed tasks as resources are moved from the performance of one task to the other. The slope of this function at any point along the curve can serve as a measure of performance substitution rate, or the amount of gain in the performance of one task that can be obtained by sacrificing one unit of performance on the other. An alternative way to look at this slope is to interpret it to represent the relative efficiency of a unit resources for the performance of the two tasks (see Navon & Gopher, in press). Study of POC curves as a major tool in the investigation of capacity interference has been recommended by Norman & Bobrow (1975, 1976).

Empirical POCs are hard to obtain because experimenters have no direct control over the way subjects allocate their resources. However, if we assume that the subject controls his own processing devices, (which is not an unreasonable assumption in view of evidence presented by Gopher & North, 1977, Sperling & Melchner, 1978), then the experimenter can try to influence resource allocation by simply telling the subject how to do it.

In other words, experimenters should allow subjects maximal control over the quality of performance on the two tasks, and induce them to change the relative emphasis on the tasks by means of pay-offs or instructions (Norman & Bobrow, 1976). However, once we obtain an empirical POC, how does it clarify the source of task interference?

The observation that improvement in performance of one task can come only at the cost of deterioration in the other one, is consistent with the notion of competition for resources from a common pool. Alternately, one could contend that greater involvement in one task produces more harmful conditions for the performance of the other one. Other possible interpretations of a POC are presented in Navon & Gopher (in press) and later in this paper. So, to support the model of central capacity, more converging operations are needed.

Testing the effect of a change in the difficulty of one task on the performance of the other may serve as another test of capacity interference. The rational is that the more difficult a task, the more it consumes resources that under the capacity interference hypothesis could otherwise be invested in the performance of the concurrent task (Kerr, 1973). When applying this method one should be careful not to ignore the importance of explicit definition and control of the priority relations between tasks. Difficulty effects may be easily confounded with considerations of allocation policy which are hard to correct.

A common convention employed to circumvent this problem is the secondary task technique, in which subjects are instructed to regard one task as primary and protect its performance against interference from the

secondary one. However, research has proven that this protection is hard to achieve. Performance on both tasks usually varies (Rolfe, 1971, Kerr, 1973). But, even if subjects can observe the instruction to protect performance on one task, then tasks are compared on just one arbitrary condition of resource allocation, namely a single point along a specific POC, plotted for one level of task difficulty. Interpretation of results is thus bound to be limited and local.

What would happen if priorities and difficulty of one task are jointly varied? Within the central capacity model, an increase in task difficulty means a decrease of resources efficiency, namely an increase in the cost per unit performance in terms of resources. Hence, more resources should now be required to achieve a specified level of performance. In terms of operating characteristics, larger sacrifice of performance on the task whose difficulty was left unchanged would now be required to release enough resources to gain a unit improvement in performance on the other task whose difficulty was increased. The result of this change will be a change in the slope of the POC function. A strict model of central capacity would therefore predict a fan-type family of POCs as a result of joint manipulation of difficulty and allocation policy. A hypothetical family of curves depicting this prediction is plotted in fig. 1 (see Navon & Gopher, in press, for a detailed discussion).

Insert Fig. 1 about here

Thus, a more promising approach to the investigation of capacity interference is to establish a complete POC for every given level of difficulty.

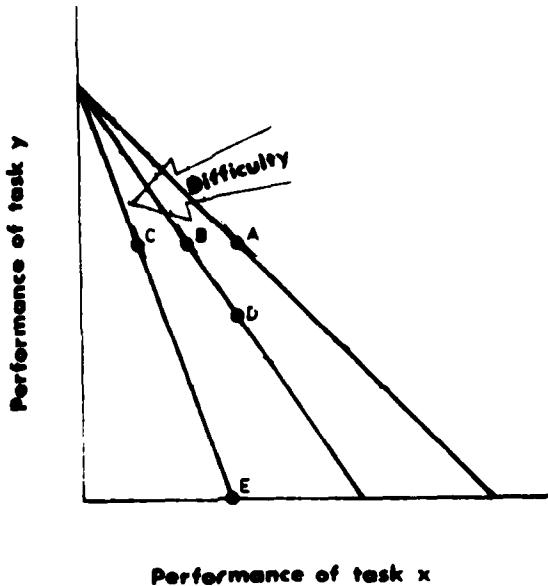


Fig. 1: A family of 'POX' curves illustrating the effect of task difficulty. The difficulty of task y is held constant while it is paired with easy, medium and difficult versions of task x. The fan-like shape of the three curves reflects the change in resource efficiency and maximal level of performance on task x as its difficulty is increased. Points A, B and C represent expected levels of combined performance, when task performance is being protected. D and E depict anticipated outcomes if performance on task x is protected.

so that the difficulty effects will be manifested in a family of POCs. This procedure enables one to test all the predictions of the capacity model: about the effects of task priorities, task difficulty and their interaction.

To apply these tests of capacity interference and jointly manipulate difficulty and priorities, we searched for a dual-task situation which the two tasks would be structurally similar, fairly complex, and apply continuous demands on the performer, so that they can be assumed to compete directly for allocation of same resources. It was decided to treat a two-dimensional pursuit tracking task as a dual task situation and consider each of the dimensions (horizontal or vertical) of tracking after the movement of a target symbol on a screen, to represent a separate task. This choice was guided by experimental data which indicated that subjects separate and react independently to performance requirement on each dimension (Elkind & Ward, 1971, Gopher, Williges, Williges & Damos, 1975, Poulton, 1974, ch. 12).

Experiment I

Method

Apparatus

A target and a control symbol were presented on a CRT display (figure 2). The target was driven in the horizontal and vertical dimensions by two independent, random, band-limited forcing functions (effective screen size was 12 x 12 cm.). The control symbol was controlled through a single two-dimensional, spring centered, hand controller. Control dynamics was a

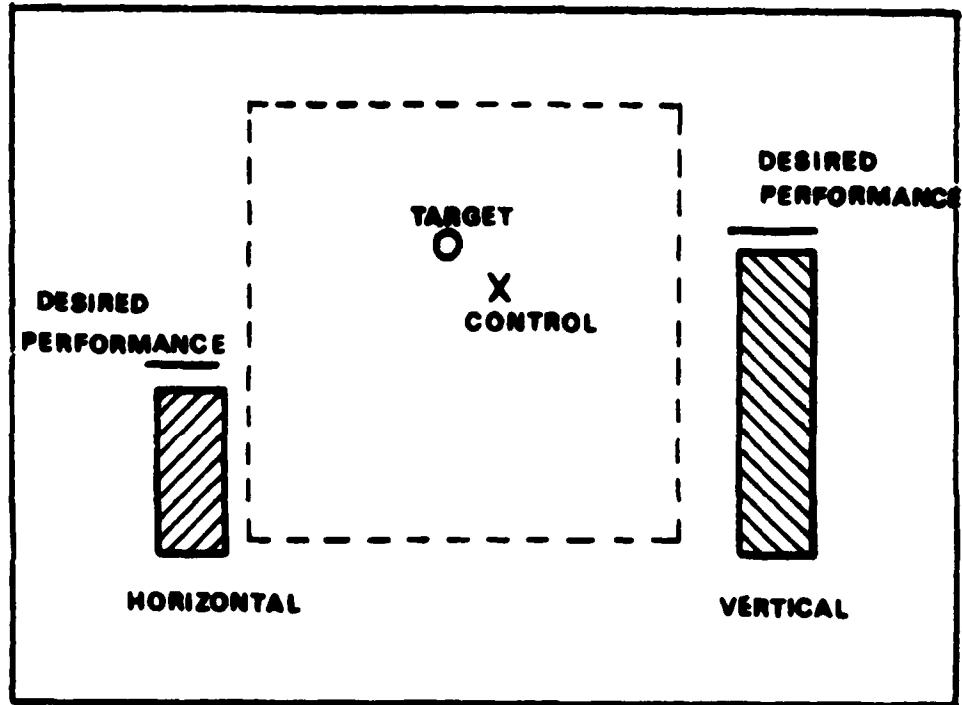


FIG. 2 - SUBJECT DISPLAY WITH FEEDBACK INDICATORS.

mixture of velocity and acceleration control (for a detailed discussion of this control dynamics, see Gopher et al., 1975, Wickens & Gopher, 1977).

Experimental control and data collection were governed by PDP 11/45 digital computer.

Difficulty Manipulation

Tracking difficulty in each dimension could be changed manually or adapted continuously by the computer through varying the location of the low-pass, first order digital filters that determined the cutoff frequency of the two target forcing functions. Increasing the value of the cutoff frequency on a certain dimension caused the target to change directions more frequently and increased the velocity of its movement.

Priorities Manipulations by Feedback Indicators

The following is a brief description of the technique developed to present performance feedback and manipulate priorities in dual-task conditions. A more detailed discussion of these techniques can be found in North & Gopher, 1976; Gopher & North, 1977. When in a fixed condition (i.e. forcing functions frequency bandwidth was not adapted), subjects were presented with an on-line, continuous feedback on their performance. Feedback indicators (one for each axis) were comprised of a short, static, horizontal line and a moving vertical bar-graph.

The static line represented the desired level of performance (in terms of tracking error), which was determined in reference to a normalized baseline distribution of performance obtained for each subject at the end of the training sessions. Subjects were asked to perform at that

level or better. The height of the moving bar-graphs reflected the momentary difference between actual and desired performance. This difference was computed by subtracting the momentary error score from the desired score and dividing the outcome by the standard deviation of the baseline distribution. Dimension priorities were manipulated by changing the required level of tracking accuracy on each dimension. Priorities were displayed by means of the height of the desired performance lines. Figure 2 depicts the display in this condition. Indicated are the tracking display, the desired performance lines and the performance bar-graphs. Note, that desired performance lines for the two axes are located at different heights, reflecting a difference in their relative priorities.

Experimental Variables

Three variables were manipulated in the first experiment: One was Task Priorities: These were manipulated by varying the minimal acceptable level of tracking accuracy on each dimension, (represented by the relative height of the desired performance lines). The height ratios used were approximately three, two, one, half, and one-third. A second independent variable was the difficulty of horizontal tracking. This was manipulated by changing the cutoff frequency for the low-pass filter applied to the output of a random noise generator to yield the target forcing function. The third variable was the difficulty of vertical tracking, manipulated in an analogous way.

Procedure

Each subject participated in five two-hour experimental sessions.

Each session was comprised of 18 three-minute tracking trials and equal periods of rest. The first three sessions were devoted to training and calibration. Adaptive procedures were employed to train subjects under increased levels of tracking difficulty. Adaptive training procedures are computerized automatic algorithms in which trainee's performance is measured and used to set the level of difficulty of the training task. This approach makes it possible to maintain performance of the student at a criterion level as he progresses at his own rate through the range of task difficulty. At the end of this phase, maximum performance measures were obtained for each subject on one and two dimensional tracking. Sessions four and five were two replications of a central composite, Response Surface design (Myers, 1971, Williges, 1973), in which tracking difficulty on each dimension and their relative priorities were jointly manipulated.

A detailed discussion of Response Surface designs is beyond the scope of this paper. However, due to its relative novelty in behavioral research, its major elements are briefly discussed. Response Surface designs enable under certain assumptions and with proper selection of experimental variables, to obtain a significant reduction in the number of experimental conditions required for a complete factorial design. The main rationale is that with proper selection of levels on each of the experimental factors, it is possible to reconstruct the structure of the variables space with minimal loss to the accuracy of predictions. Naturally, Response Surface designs are most cost effective in multifactors experiments.

Experimental variables included in a Response Surface design should

be quantifiable and measurable such that the only constraints on the selection of experimental levels are those dictated by design considerations. Five levels have to be selected on each variable. Their raw levels are properly transformed to a standard common linear scale to represent the levels ± 1 , -1 , 0 , $\pm\alpha$, $-\alpha$ of this scale. Alfa levels represent the extremes of the range of interest on every experimental variable (say, the highest and lowest values of target movement frequency), and their representative standard score value, depends on the number of factors in the experiment, the number of replications of each experimental condition and additional design considerations. For a K factors design, the method requires to sample $2^K + 2^K + 1$ experimental condition out of the total number of possible continuations, should we conduct a complete factorial design with 5 levels on each factor. (In the present three factors experiment, 15 out of the possible 125 combinations are sampled.) Table 1 lists the 15 conditions by their specific combination of standard scores levels. Alfa was assigned a standard value of 1.68. The three variables are Target Horizontal Frequency (Freq. X), Target Vertical Frequency (Freq. Y) and Task Priority (Prior.).

(Insert Table 1 about here)

To define a meaningful range of tracking difficulty on each dimension, it was decided to use for each subject the final levels of tracking difficulty, obtained by him in two dimensional tracking during training as the center points of the difficulty range (0,0). Lower and upper levels for this range ($\pm \alpha$) were determined by adding and subtracting from these values the maximum levels obtained when each

TABLE 1

The fifteen experimental conditions (standard score levels, $\alpha = 1.682$).

Experi- mental variables	Experimental Conditions														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Freq.x	1	1	-1	-1	-1	1	1	-1.68	0	0	1.68	0	0	0
	Freq.y	-1	1	1	-1	1	-1	-1	1	0	-1.68	0	0	1.68	0
Prior.*	1	-1	1	-1	-1	1	-1	1	0	0	-1.68	0	0	1.68	0

*Positive values horizontal tracking higher priority.

dimension was performed singly. The selected range for manipulation of priority was .25 - .75 (the five raw levels on this variable were therefore .25, .35, .50, .65, .75). Two dimensional tracking with equal priorities (.5) served as the center point on this factor.

Desired performance levels (namely the height of the desired performance lines on the display) were determined from the priority values in the following way: a priority level of, say, .75, on a certain dimension, corresponded to a level of performance that assumed the 75 percentile in the baseline distribution of performance of that subject. That is, an instruction to put priority of .75 was actually a requirement to perform at a level better than the lowest 75 percent of the baseline performance levels. Other levels of desired performance were obtained in a similar way. Thus, in both manipulations of difficulty and desired performance, the set of variable levels employed for different subjects could differ physically but presumably had the same psychological meaning across all subjects.

Subjects

Five male, right-handed subjects participated in the first experiment. Subjects were paid hourly rates for their participation.

Results

Report of experimental results concentrates on the data obtained during the last experimental session. Root Mean Square (RMS) tracking error on each tracking dimension (vertical and horizontal) served as the main performance measure. Tracking errors on each axis were measured

every 60 msec. and integrated over 15 second intervals. The 12 values obtained in this manner for each 3 minute trial were averaged to yield an overall performance score for that trial. Each of the three minute trials represented one of the 15 experimental conditions listed in Table 1.

Consistent with the analysis conventions of Response Surface designs, two standard statistical analyses were conducted on the data occurred for the five subjects in the performance of the 15 experimental conditions. First, a least squares, second order, multiple regression equation was fitted to the data to determine the first and second order effects of the three independent variables on tracking accuracy. Then, an analysis of variance was applied to test the reliability of the obtained regression coefficients. Separate analysis was performed for vertical and horizontal tracking accuracy.

Tracking accuracy on the horizontal axis revealed both first and second order effects of task priority on tracking RMS error. (For the first order effect $F = 157.8$, df 1/65, $P < .001$. For the second order effect $F = 31.6$, df 1/65, $P < .001$). A change in tracking difficulty on the horizontal or vertical dimensions did not have reliable first order effects on horizontal accuracy, but small second order effects of both manipulations were observed ($F = 3.93$, df 1/65, $P < .06$ for horizontal difficulty. $F = 6.20$, df 1/65, $P < .05$ for vertical difficulty.) None of the interaction terms between the three experimental variables reached statistical reliability. The joint effect of the three variables on horizontal tracking accuracy yielded a multiple regression coefficient of $r = 0.71$ or 50.8 percent accounted variance ($F = 21.9$, df 9/65, $P < .001$).

Similar pattern of results was obtained for vertical tracking performance. Task priority had strong first and second order effects (for the first order component $F = 158.7$, df 1/65, $P < .001$; for the second order component $F = 16.48$, df 1/65, $P < .001$). Here again, difficulty manipulations had much smaller effects, although reliable first order effect was obtained for manipulation of target frequency on the vertical axis ($F = 4.46$, df 1/65, $P < .05$). The multiple regression score for this dimension yielded somewhat higher correlation coefficient $r = 0.77$, accounted variance 59.1 percent ($F = 22.2$, df 9/65, $P < .001$). Before further examination of these results is attempted, note the large effect of task priority on both axes. This outcome supports the initial argument that subjects can respond separately to the two tracking dimensions, and is also compatible with reports of subjects. Another evidence along these lines came from the analysis of the Euclidian error scores ($\sqrt{(RMSX)^2 + (RMSY)^2}$); these were calculated to test the hypothesis that rather than responding separately to each dimension, subjects respond directly to the integrated two dimensional Euclidian distance. Euclidian error scores proved to be a poor measure of subjects' performance. Only 26 per cent of the experimental variance was accounted for by the second order multiple regression equation calculated for this dependent measure, as compared with 51 and 59 per cent that were obtained for the separate measures. It appears safe to conclude that subjects were indeed capable of reacting to the two tracking dimensions as separate, concurrently performed tasks.

Effects of manipulating priorities

In the following section we take a closer look at the effect of task priority by plotting together the regression function of this variable on vertical and horizontal tracking accuracy. Figure 3 shows the separate effect of priorities on each axis in the two dimensional situation. The abscissa in this figure represents priorities in favor of the horizontal dimension ($PrY = 1-X$). The ordinate depicts tracking accuracy (expressed as $1 - \text{RMS error}$). Each of the two curves was fitted by averaging across the different levels of task difficulty. Actual means for the five priority levels employed in the experiment are depicted by x's and dots.

Three important features can be observed in this figure: first, the effect of priorities is large; its overall range is about 13 per cent of scale RMS error. Second, the effect is quite symmetrical on the two axes. Third, the effect is negatively accelerated. Emphasizing a dimension too much is not necessarily productive. It may even be a little disruptive as seems to be the case with the horizontal dimension (where the performance curve has a downward bend at the highest priorities).

(Insert Fig. 3 about here)

What is the joint impact of the above effects on overall tracking efficiency in the two dimensional situation? This effect is depicted in figure 4. The sum and difference functions presented in this figure were obtained by adding and subtracting the tracking error scores for the two axes in each of the priority combinations presented in figure 3. Figure 4 depicts a perfectly linear difference function which indicates the faithful

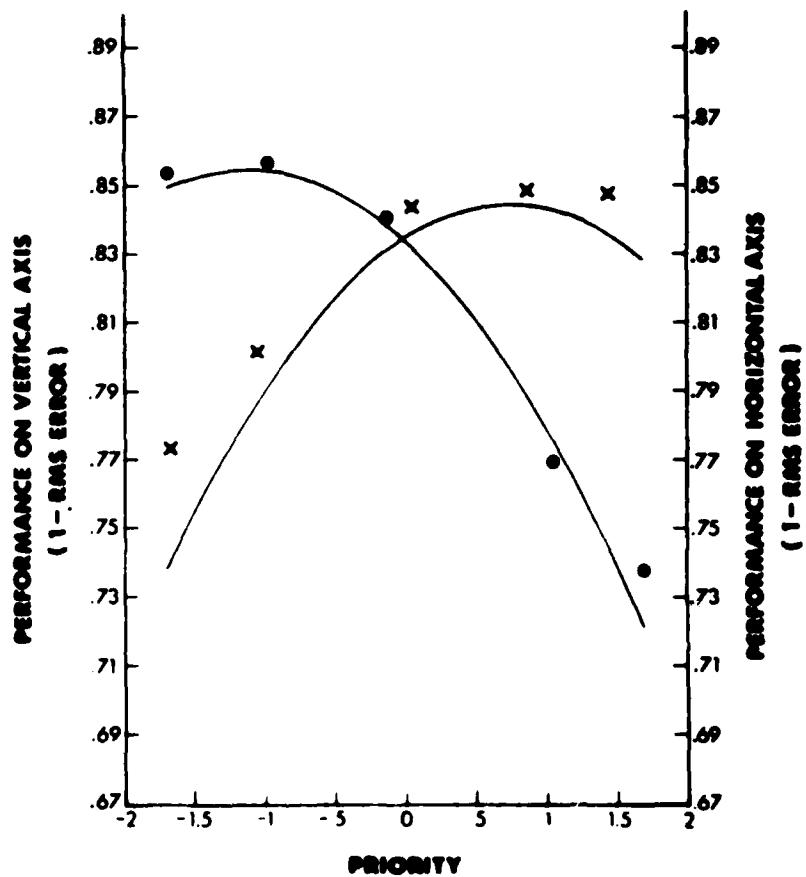


Fig. 3: Effects of task priority on horizontal and vertical tracking accuracy (vertical priorities are expressed as 1-x. Accuracy is presented as 1-RMS Error). Dots represent mean actual data.

(Insert Figure 4 about here)

responsiveness of subjects to the instruction to change priorities. But, it is also evident that they were much more successful in adjusting to the lenient tolerance level associated with reduced priorities, than with the stringent requirement when priority was increased. This differential success is clearly revealed in the curvilinear sum function which suggests that joint performance was maximized when both dimensions are attended to about equally well.

Finally, we can examine the effects of manipulating priorities on the tradeoff of performance between the tracking dimensions by constructing POC functions. Figure 5 presents the average POC fitted to the present data by jointly solving the two regression equations for different values of priority, averaging across levels of tracking difficulty.

(Insert Figure 5 about here)

The solid line is the one fitted to the data of all subjects. Dots represent mean actual data for the five priority levels. Performance Operating Characteristics is highly convex, indicating only little tradeoff between dimensions, limited to a narrow region of the performance range. The strong curvature of the POC suggests that if task interference is due to central capacity interference, performance cannot be linear in amount of invested resources.

Manipulation of tracking difficulty: Difficulty manipulations, as conducted by varying the cutoff frequency of target movement on the two

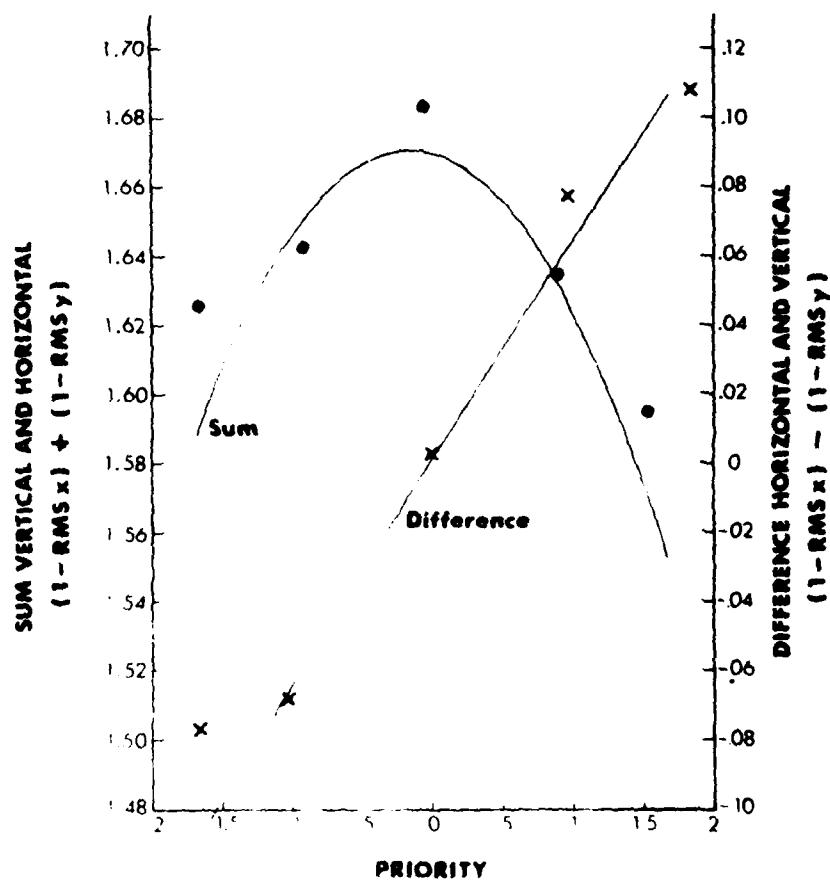


Fig. 4: Sum and difference curves of tracking accuracy scores on the vertical and horizontal dimensions as a function of priorities. Dots represent mean actual data.

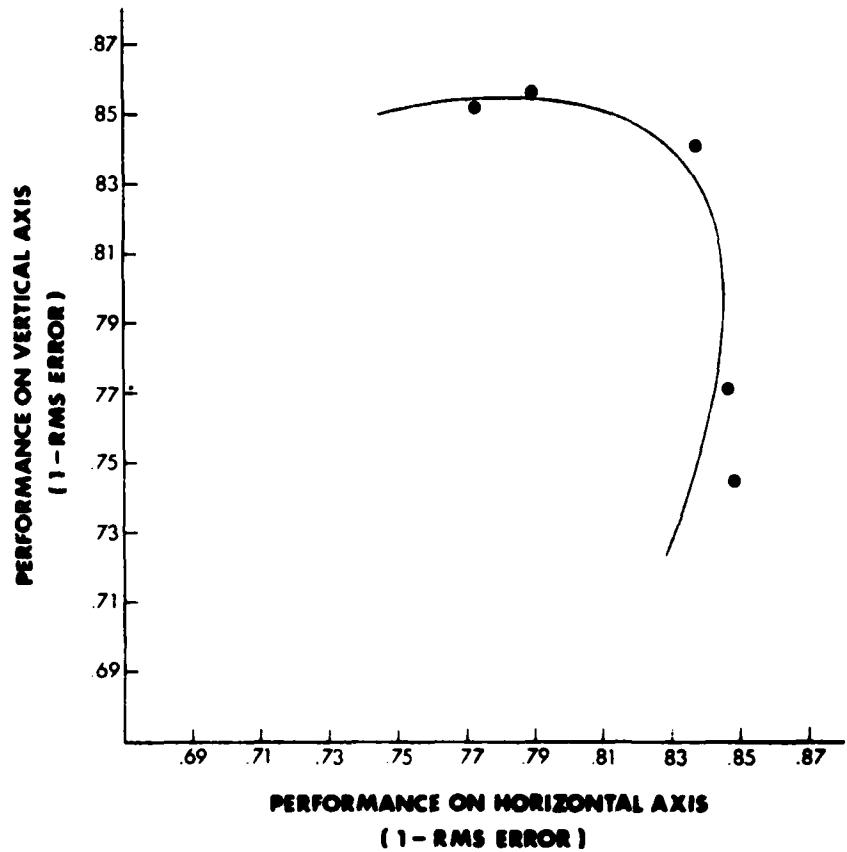


Fig. 5: POC curve depicting performance tradeoff between horizontal and vertical tracking as a function of change in their relative priority.
(Average across manipulations of target frequency).

axes, had much smaller effect on tracking accuracy. Although reliable, the relative magnitude of the regression coefficients obtained for difficulty manipulation were about one fourth of those obtained for task priorities. (Direct comparisons of these coefficients are legitimate because all raw levels were transformed to a common scale). With such weak effects, construction of a family of POCs, where each curve describes a different combination of tracking difficulty, is not expected to yield a wide spread between the curves. Also, because none of the interaction terms between frequency and priorities reached statistical reliability, the shapes and slopes of POCs are not expected to change in different configurations of tracking difficulty. The results of this first experiment do not encourage a detailed analysis of the interactive effects of difficulty and priority manipulations. To clarify this argument, five POCs, plotted for different levels of vertical tracking difficulty and average horizontal tracking difficulty are presented in figure 6. All curves have the same shape, the most distant points

(Insert Figure 6 about here)

between curves are about 6 per cent of scale apart. In addition, the easy task crosses both the medium and the hard configuration reflecting the reliable second-order effect of vertical difficulty on horizontal tracking accuracy, an outcome which cannot be accommodated by a simple interpretation of resource allocation and will be elaborated in the discussion.

Discussion

Among the three experimental variables, priorities had the greatest effect on performance. However, subjects reduced their tracking accuracy on the axis whose priorities were lowered, but were unable to use the "released resources" to improve performance on the other dimension, whose desired performance was simultaneously increased. Several alternative interpretations for this outcome may be considered.

One possibility is that, contrary to our assumption, subjects did not perceive each of the tracking dimensions as a separate task, but responded to the two-dimensional tracking task as a single integrated whole. According to this approach, the reason that Euclidean accuracy in two-dimensional tracking is worse than accuracy in unidimensional tracking (Poulton 1974, Ch. 11) is not that two-dimensional tracking is composed of two time-shared processes, but that it involves uncertainty about orientation of motion. Note that larger Euclidean error does not require that the horizontal and vertical components of this error be higher than the corresponding errors in unidimensional tracking. Thus, the apparent minute interference between the two tasks revealed in the present results may be just a reflection of the fact that there are no two tasks: the whole (two-dimensional tracking) is not the sum of its parts (one-dimensional trackings). However, in the present manipulation, the only experimental condition which could be effectively controlled with such response strategy is equal priorities. In all other conditions, the subject is forced to treat each dimension separately. If, in those conditions, subjects do behave as if they time-share two unidimensional

tracking tasks, then the puzzle presented by the findings still remains: why deterioration in performance of one task is not accompanied by commensurate upgrading of performance of the other one.

An alternative explanation is that the limited tradeoff is due to a ceiling dictated by the nature of the task: subjects simply could not reduce tracking error below a certain level, say .15 - .16 RMS error, no matter how easy the task was, and how much resources were available. But, if this interpretation is true, we should expect an interaction between difficulty and priorities, such that the ceiling will be effective only in easy tracking conditions. Yet, no interaction between difficulty and priorities was found in the analysis of variance. Different difficulty conditions (as plotted in Figure 6) changed the asymptotes of tracking performance but did not affect the general shape of the POC curves. One's confidence in the rejection of the ceiling interpretation would have been greatly enhanced if the difficulty manipulation employed in the present experiment would have had a larger effect of performance, without the odd curvilinearities that were observed on the horizontal axis. The identical shape of POCs in different difficulty configurations will then serve as a conclusive evidence against the ceiling interpretation. With the mild effects observed in the present data, rejection of this alternative is tentative.

A third possibility is that the former two interpretations have looked at the problem from a wrong perspective. Perhaps the issue is not why one gains less and less by emphasizing the performance of a task more and more, but rather why we lose very little on one task while adding

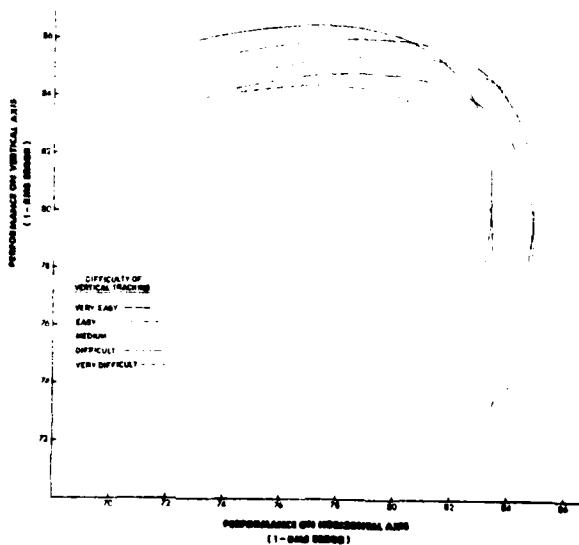


Fig. 6: A family of POCs representing tracking accuracy (1-Root Mean Square Error) on each of the axes in dual-axis tracking as a function of task emphasis. Each POC corresponds to a different level of difficulty (target frequency) of vertical tracking, and is obtained by jointly solving two second-order multiple regression equations for predicting performance on the two axes from the task emphasis variable.

another one. The two tasks may not interfere very much with each other, so that adding one task on top of the other one (or requiring to perform the first one better) does not withhold a lot of relevant resources from the second one, and conversely degrading the performance of the first one does not release a lot of relevant resources.

Thus, we come back to the notion of single pool of limited resources. We confronted the two tracking dimensions to demonstrate linear tradeoffs as emphasis is moved from one task to the other. If it is accepted that the resultant POCs reflect performance tradeoff in a resource limited region (Norman & Bobrow, 1975), then one plausible conclusion is that the resources consumed by the two tasks are fairly disjoint. The single capacity notion is replaced by a multiple capacity approach, an idea recently voiced by several investigators (Navon & Gopher, in press; Wickens, 1978). The curvilinear effect of the difficulty of one dimension on the performance of the other may be interpreted as another indication for a lack of capacity interference between the axes, because the central capacity model would predict a monotonous effect.

An assumption of disjointed resources in the particular case of horizontal and vertical tracking is somewhat embarrassing. If vertical tracking does not share resources with horizontal tracking, then what is the nature and how specific are these resources?

A conclusion that resources are numerous and specific constitutes a morbid deviation from the parsimonious notion of central limitation and should therefore be examined with extreme caution. It should be

supported by comprehensive experimentation and unambiguous data. The main deficiency of the present data is that the difficulty manipulation was not effective enough so that only one of the two tests of capacity interference proposed in the introductory section could be successfully applied. Conclusions are inevitably limited and require to identify proper difficulty variables that positively tap the locus of difficulty on the tracking task.

Two explanations can be offered to account for the ineffectiveness of the present difficulty manipulation. One is methodological. It is possible that manipulating the cutoff frequency of the low-pass filter has only marginal effect on the band of target frequencies. Hence, large displacements of the filter may actually result in only moderate change of task difficulty (as reflected in tracking accuracy). In view of the small performance difference between single and dual axis tracking revealed in our data, the procedure employed to define the range of task difficulty may have restricted the impact of this manipulation on performance.

Another explanation is related to the theoretical nature of the difficulty parameter. Results of several tracking experiments seem to suggest that tracking tasks are primarily loaded on the response selection and response execution stages (e.g. Trombo, Noble and Swink, 1967; North, 1977; Wickens, Israel and Donchin, 1977). It follows that tracking accuracy should be more sensitive to difficulty variables which correspond to these stages. Within our paradigm of pursuit tracking, manipulation of target frequency can be more closely linked with stimulus processing and encoding side rather than with the two response stages. When target

frequency is manipulated, response patterns and response complexity are basically left unchanged (unlike, for example, a change in control dynamics or control gain, see Gopher et.al, 1975). Thus, the reduced impact of the target frequency manipulation can be explained on grounds of its secondary relevance to the locus of load in tracking performance.

In order to test the two explanations and consistent with our desire to obtain more viable joint effects of difficulty and priorities, the first experiment was repeated in two additional, independent groups of subjects with different manipulations of task difficulty. For one group, the velocity of target movements was directly manipulated.

In the second group, control dynamics (representing a response-related variable) was varied to manipulate task difficulty.

Experiment 2 - Manipulation of Target Velocity

Method

Experiment 2 replicated the design and procedures of the first experiment. The only change was in the manipulation of task difficulty. Target velocity on each dimension was directly varied to serve as the task difficulty parameter. The extreme levels on this manipulation ($\pm \alpha$ values in the RSM design) were velocity levels representing 30 per cent increase and decrease from the final levels obtained by each subject during the three adaptive training sessions. This procedure resulted in some increase of the general difficulty of the task. Target forcing function frequency on each dimension was fixed at the .7 Hz level. Control dynamics, as in the first experiment, was mixed velocity and acceleration controller. A group of five male, right-handed students participated in the experiment.

Results and Discussion

Presentation of results concentrates again on the data obtained in the last experimental session, where task difficulty and axes priorities were jointly manipulated. Separate regression equations and analyses of variance were performed on the RMS error scores obtained for vertical and horizontal tracking.

In this experiment again, and on both axes, the task priority variable had reliable first order effects on tracking accuracy. Second order effects were reliable on the vertical axis and approached reliability for horizontal tracking accuracy. (On the horizontal axis: first order effect, $F = 41.5$, df 1/65, $P < .001$, second order effect, $F = 3.2$, df 1/65, $P < .10$. On the vertical axis: first order effect, $F = 36.63$, df 1/65, $P < .001$, second order effect, $F = 7.68$, df 1/65, $P < .01$). However, the magnitude of these effects as reflected in the multiple regression coefficient was about half of those obtained for this variable in the first experiment. Table 2 presents the regression coefficients of the two experiments. Manipulation of tracking difficulty had signifi-

(Insert Table 2 about here)

cant linear (first order) effects on both tracking dimensions (on the horizontal axis, $F = 10.43$, df 1/65, $P < .01$, on the vertical axis, $F = 28.6$, df 1/65, $P < .001$.).

The range of performance change as a result of difficulty manipulations in this experiment was much larger than those observed in the first experiment. Manipulation of target velocity accounted for 7 per cent

TABLE 2: REGRESSION COEFFICIENTS FOR MANIPULATION OF TASK PRIORITIES
IN EXPERIMENTS 1 AND 2

Regression Coefficients (for standard scores)			
		<u>First ord. effect</u>	<u>Second ord. effect</u>
Exp. 1	Horizontal	2.68	1.80
	Vertical	3.74	1.81
Exp. 2	Horizontal	1.51	0.63
	Vertical	1.30	0.89

and 17 per cent of the variance in tracking accuracy on the horizontal and vertical axes respectively. In the first experiment only 2.6, and 1.3 per cent of variance were contributed to the variance in horizontal and vertical tracking accuracy by the two difficulty manipulations. In addition, no curvilinear effects were revealed and each difficulty variable only affected performance on the axis on which it was applied. As in the first experiment, none of the interaction terms between the three experimental variables was statistically reliable. The multiple correlation coefficients for the effects of the three experimental variables on performance were .60 and 0.66 for horizontal and vertical tracking respectively. ($F = 6.43$ and 8.37 , for horizontal and vertical axes, $df = 9/65$, $P < .001$).

Figure 7 depicts the average POC fitted from the multiple regression equations (averaged across subjects and difficulty manipulation).

(Insert Figure 7 about here)

The POC assumes the same convex shape observed in experiment 1, reflecting only limited tradeoff between axes. Note the reduced range of performance change.

With the improved manipulation of task difficulty, we can now also explore more meaningfully the joint manipulation of difficulty and priorities. In Figure 8, five POCs are plotted. Each curve represents one difficulty level of vertical tracking, while horizontal difficulty is averaged over all levels employed.

(Insert Figure 8 about here)

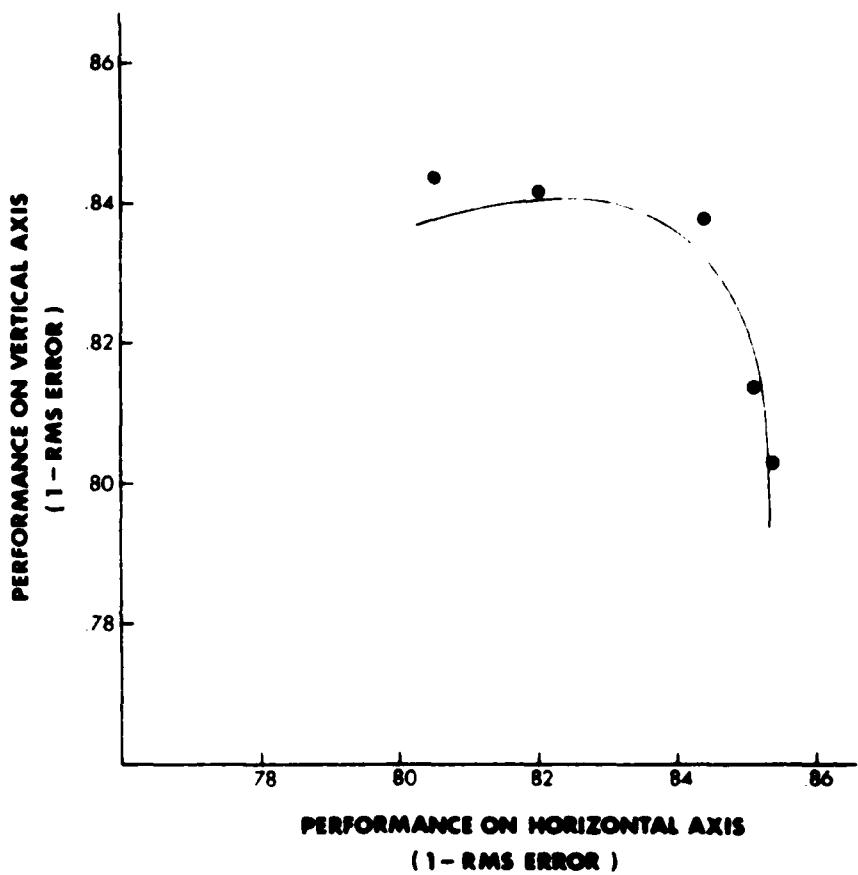


Fig. 7: POC curve depicting performance tradeoff between horizontal and vertical tracking as a function of change in their relative priority. (Averaged across manipulation of target velocity). Dots represent mean actual data.

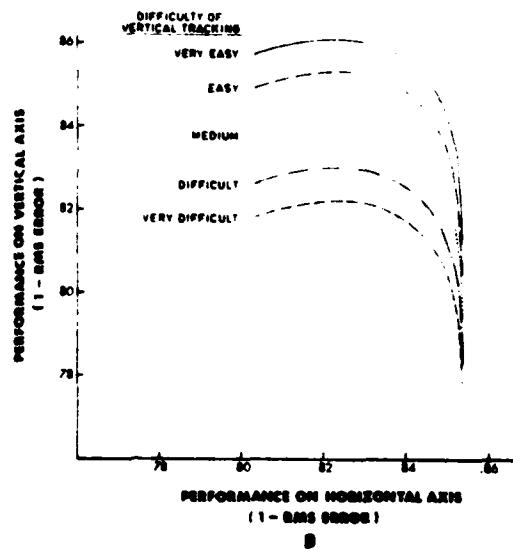


Fig. 8: A family of POCs representing tracking accuracy on each of the axes in dual-axes tracking as a function of task emphasis. Each POC corresponds to a different level of difficulty. (Target velocity manipulations).

All five curves assume the same general shape which closely resembles the average POC. Decreasing the level of tracking difficulty on the vertical axis did not change the slopes or shapes of the respective POCs. (Similar results can be plotted for fixed levels of vertical difficulty and different levels of horizontal tracking). POC's asymptote at a lower level for increased levels of vertical difficulty, as the priority of this axis is increased. Distance between functions on the horizontal performance axis remain unchanged as its difficulty was constant. Despite the evident effect of difficulty on subjects' tracking performance, changing the velocity of target movements on one axis did not affect the extent of the tradeoff between axes.

These results clearly disconfirm the central capacity model prediction of fan-like family of POCs which reflects the anticipated interaction between task difficulty and resource allocation.

They seem to overrule the ceiling effects interpretation, because such ceiling should affect only the easier tracking conditions and disappear when task difficulty is increased.

Experiment 3 - Manipulation of Control Dynamics

Method

Five male, right-handed students served in this experiment. Experimental design and procedures generally replicated those of experiments 1 and 2. The only difference was in the parameter selected for manipulation of tracking difficulty on vertical and horizontal tracking. Control difficulty was systematically manipulated by adding increasing

proportions of second order (acceleration) determinants to the transfer functions of the hand controller, thereby incrementing tracking difficulty. Control dynamics generally followed the equation:

$$(1) \quad \theta = (1-\alpha) \frac{.75}{s} + \alpha \frac{.3}{s^2}$$

Theta in the left hand side of this equation represents control system output. The two right hand terms s and s^2 represent the velocity and acceleration components in system response. s is the Laplace transform and can be generally replaced in a continuous time dependent function by the derivative $(\frac{d}{dt})$. In a velocity system, position displacements of the hand controller would change the speed of the controlled system, while in an acceleration system changes in controller position would affect the rate of change in system speed of movement. Alfa values in equation 1 were manipulated to vary the relative contribution of velocity and acceleration to system response. It is easy to observe that when α equals 0, the second term disappears and the systems react as a pure first order velocity controller. When α equals 1 the system becomes a pure second order acceleration controller, an unstable system which is very difficult to control. (Because an increment in the level of α increases the effect of the acceleration component, the task difficulty parameter in this experiment has been named Acceleration). During the three preliminary training sessions subjects practiced this variable adaptively until they reached their maximal level on single and dual axis tracking. As in the second experiment the manipulation range on this variable was defined as 30 per cent increase and decrease of the final

level reached by each subject at the end of training. This procedure brought again an average increase in the general difficulty of tracking as compared with tracking in the first experiment.

Results and Discussion

Among the three difficulty manipulations investigated in the present study, changing control dynamics appears to create for subjects the most demanding configuration to cope with. This increased difficulty was reflected in an increased instability and noise in the measurement of performance and larger effects of individual variability. As a result, multiple correlation coefficients for the regression equations computed on vertical and horizontal tracking scores decreased to 0.48 and 0.57 respectively. Still, the analysis of variance showed high reliability for both coefficients. (For horizontal tracking, $F = 6.01$, $df = 9/65$, $P < .001$. For vertical tracking, $F = 8.45$, $df = 9/65$, $P < .001$). Task priority had reliable first order effect on horizontal tracking accuracy ($F = 17.18$, $df = 1/65$, $P < .001$), but no second order effect. On the vertical dimension first order effect was highly reliable ($F = 50.05$, $df = 1/65$, $P < .001$), and second order effect approached statistical reliability ($F = 3.92$, $df = 1/65$, $P \approx .06$). Clearly, the main effect of priority on tracking performance in both axes is linear and the curvilinearity contributed by second order components in the first two experiments almost disappeared. The overall range of performance change contributed by priority manipulation resembled the range observed in the second experiment and was much narrower than the range obtained in the first experiment. The standard regression coefficients for the first

order effect on horizontal and vertical tracking were 0.93 and 1.14 respectively. Control dynamics turned out to be a strong and effective manipulation of task difficulty. Highly reliable first order effects were observed for this manipulation on both axes. (For horizontal tracking: $F = 29.69$, df 1/65, $P < .001$. For vertical tracking: $F = 17.51$, df 1/65, $P < .001$). No second order effects were found.

In addition to the direct effects of difficulty and priority, in this experiment a noticeable effect of interaction between resource allocation (priority) and task difficulty was revealed on the vertical dimension, and approached the common level of statistical reliability ($F = 3.23$, df 1/65, $P < .09$).

Figures 9 and 10 present the average POC and a family of POCs plotted for these results. It is evident from looking at these figures

(Insert Figures 9, 10 about here)

that within the relatively shrunken performance range presented in Figure 9, tradeoff between the two tracking axes is close to linear. The interaction between difficulty and priority is clearly manifested in the fan-like family of POCs presented in Figure 10. As tracking difficulty on the vertical axis is decreased, the slope of the POC curve increases. It is in this last experiment that the central capacity model prediction of interaction between task difficulty and priority was borne out.

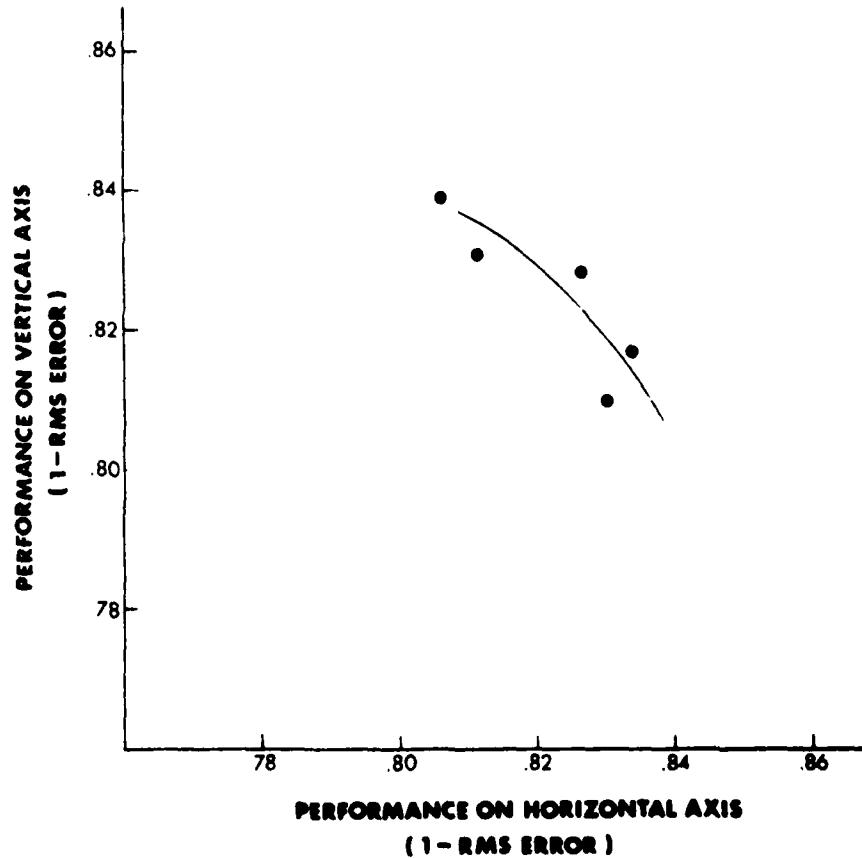


Fig. 9: POC curve depicting performance tradeoff between horizontal and vertical tracking as a function of change in the relative priority. (Average across manipulations of control dynamics). Dots represent mean actual data.

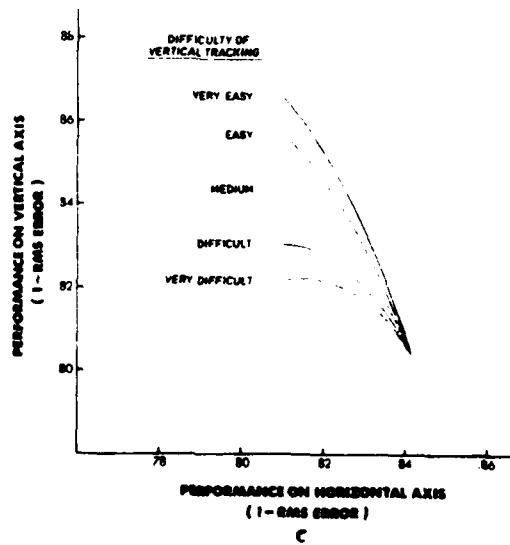


Fig. 10: A family of POCs representing tracking accuracy on each of the axes in dual-axes tracking as a function of task emphasis. Each POC corresponds to a different level of difficulty. (Control dynamics manipulations).

General Discussion

Of the three experiments reported here, only the results of the last one are consistent with the predictions of the central capacity model as developed in the introductory section of this paper. The highly convexed POCs obtained in the first two experiments do not support the anticipated effect on performance of change in task emphasis, resulting from reallocation of resources from a common limited pool. Subjects were not capable of improving their performance on one tracking dimension, while performing at a lower level on the other one. In addition, manipulation of task difficulty on each dimension affected the level of performance on that dimension, but did not interact with task emphasis, or influenced monotonically the level of performance on the other dimension. Both interaction and monotonous effects are predicted by the central capacity model. But, this is half of the story, because the expected linear effects and indications of the anticipated interaction between difficulty and priorities, which are consistent with the model, were revealed in the third experiment, although the only variable changed in it, compared with the other two, was the type of difficulty manipulation employed.

How can the discrepancy between those results be interpreted? Ceiling effects seem to be an unsatisfactory interpretation for the convexed POCs observed in the first two experiments, because similar convex shapes were obtained for easy and difficult configurations of tracking (exp. 2). Another possible interpretation along these lines is that, in contrast with the third experiment, the tracking task in the first two experiments was so easy that the central pool of resources was not

exhausted before performance reached its data limitation (Norman & Bobrow, 1975). This interpretation is unlikely in view of the general increase of tracking difficulty in the second experiment, which was not accompanied by any change in the curvature of the POC.

In light of the present results, our initial approach to the concept of resource limitation and the selection of experimental tasks may be oversimplified and may need some revision. Tracking along single dimension may not be as unidimensional and simple. It can still be broken into several task components that impose differential processing demands. Capacity may not be that general and undifferentiated pool depicted in our initial discussion.

Consider an alternative concept in which the human processing system is assumed to have a number of mechanisms, each having its own capacity and those capacities can at any moment be allocated in different proportions among several processes. Then, different types of difficulty manipulations can affect differentially the use of each of those capacities. (For a detailed exposition of multiple capacity approach, see Navon & Gopher, *in press*). Within such framework, we can consider a post-hoc account that accommodates the data nicely. Suppose that, despite the apparent similarity between vertical and horizontal tracking, they do not call exactly for the same types of resources. Furthermore, suppose that the two tasks require the same kind of motor-related resource, but different kinds of perceptual or "computational" resources. In the first two experiments, the load on the motor system (the common resources) was relatively small, because control dynamics was primarily first order

and easy to handle, hence the tasks did not interfere very much with each other. However, with the increased complexity of the control dynamics in the third experiment, both tracking dimensions required more motor capacity in all experimental conditions, so that they had more to compete for. The discrepancy between the data of the three experiments may be understood if we realize that the only parameter which seems to affect the motor system is the control dynamics manipulation. Manipulations of target frequency and velocity of movement did not increase the general difficulty of system control and therefore did not affect the resource utilization of the common resource, and had little impact on the tradeoff between vertical and horizontal tracking. The multiple capacity interpretation is only post-hoc and preliminary. It requires systematic investigation and examination of a wider battery of tasks. Hopefully, if the human processing system is a multiple resource system, the number of these resources is limited, or we would reach a state of despair. It is also clear, however, that even if the less parsimonious multiple resource model is not required, and we can maintain the simple central capacity notion, this concept should be reconsidered and thoroughly tested. We hope that the present research pointed to some of the conceptual ambiguities and outlined directions of experimental tests.

One final point to be noted in the present results is the reduced effect of the priority variable in the second and third experiments as compared with the first experiment. As task difficulty was generally increased in these latter two experiments, the shrunken range of effects of the priority variable can be interpreted to reflect the reduced effect

of resources allocation on performance when their efficiency is low, that is, when the task is difficult and the resource cost per unit performance is high. Conversely, when a constant amount of resources is withdrawn from the performance of a certain task, easy task would reveal more deterioration than a difficult one. Bartell and Kantowitz (1978), in a recent study, proposed similar interpretation to the larger decrements of performance observed on their easier task under time-sharing conditions.

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